3.3 Disturbance Working Group

Version 23 March 2016

Projects with fire disturbance as a primary theme (titles and links to profiles)

Legacy Carbon: combustion and its consequences

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Xanthe Walker (Northern Arizona University)
Merritt Turetsky (University of Guelph)
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2014 NWT Wildfires

Laura Bourgeau-Chavez (Michigan Technological University)
Nancy French (Michigan Technological University)
Sarah Enders (Michigan Technological University)
Evan Kane (Michigan Technological University)

Tundra Fires

Tatania Loboda (University of Maryland)
Liza Jenkins (Michigan Technological University)

Scaling wildfire climate forcing

Brendan Rogers (Woods Hole Research Center)
Scott Goetz (Woods Hole Research Center)
Sander Veraverbeke (University of California-Irvine)

Additional projects with a disturbance theme

Tundra fire carbon and energy exchange

Adrian Rocha (University of Notre Dame): funded by NSF LTERB program

Impacts of fire on hydrological connectivity in permafrost landscapes

Rob Streigl (USGS)

Incorporating a dynamic fire regime into earth system models

Dan Hayes (University of Maine)

Winter soil C efflux in burned ecosystems

Sue Natali (Woods Hole Research Center)

Post-fire vegetation impacts on climate forcing

Mike Goulden (University of California-Irvine)

Other projects that joined after WG report was finalized

Any ABoVE project should include acknowledgement of disturbance because it is a major structuring factor for all high northern latitude ecosystems. We will include more specific projects here as they are selected or affiliated as ABoVE projects.
Schaefer YKD project

3.3.1 OBJECTIVES

Overview: One of the most rapid pathways by which climate warming is altering the structure and function of high northern latitude ecosystems is through intensification of wildfires. The fire disturbance working group seeks to document changes in wildfire patterns and impacts within the ABoVE region and to understand the consequences of these changes for carbon (C) biogeochemisty, permafrost, hydrology, flora, fauna, and the goods and services that Arctic and boreal ecosystems provide to both local residents and global stakeholders in the climate system. The ABoVE Campaign is (loosely) structured around resilience theory, so all projects in this working group focus on (or at least allude to) the task of identifying key sources of resilience in arctic-boreal systems: interactions and feedbacks that reinforce system-level recovery to historic state in the face of changing fire disturbance impacts. Similarly, projects seek to identify factors that are likely to push ecosystems beyond historic boundaries and drive state changes that have lasting impacts on local, regional, and even the global land-atmosphere system.

Combustion of the soil organic layer is paramount theme in all projects of this working group because this event determines the impacts of fire on all major ABoVE thematic areas. The majority of organic C sequestered in arctic tundra and boreal coniferous forests and peatlands resides in thick soil organic layers (SOL) that can be thousands of years old, a C legacy of past fire cycles (Harden et al. 2000). Combustion of the SOL dominates C emissions during fire (Kasischke et al. 1995, Boby et al. 2010a), and more intense fires result in deeper burning (Turetsky et al. 2011). Because rates of soil C accumulation vary across the landscape (Hobbie et al. 2000), deeper burning may not always combust legacy C. But deeper burning that does combust legacy C could rapidly shift ecosystems across a C cycling threshold: from net accumulation of C from the atmosphere over multiple fire cycles, to net loss. At regional scales, net C loss from boreal and tundra ecosystems will amplify C cycling feedbacks to global climate.

Disturbances that impact the SOL can also persistently alter both physical and biological controls over C cycling (Johnstone et al. 2010a), including permafrost integrity and hydrology. Reduction or loss of the SOL decreases ground insulation (Shur and Jorgenson 2007, Jorgenson et al. 2013), warming permafrost soils and exposing organic matter that has been frozen for hundreds to thousands of years to microbial decomposition, mineralization, and atmospheric release of greenhouse gases (Schuur et al. 2008). Degradation of permafrost can also increase or decrease soil drainage, leading to threshold changes in soil moisture regimes that impact both decomposition and production processes (Schuur et al. 2009, Jorgenson et al. 2013). Loss of the SOL also exposes mineral soil seedbeds (Johnson 1996, Johnstone et al. 2009) leading to recruitment of species that do not establish readily on organic soil, such as deciduous trees in broeal forest (Johnstone and Chapin 2006) or tall deciduous shrubs in tundra (Lantz et al. 2009, Pizano et al. 2014). These recruitment events can shift post-fire vegetation to alternate successional trajectories (Johnstone et al. 2010b) that differ strongly from pre-fire plant communities in forage quality and ecosystem services provided to local residents. Plant-soil-microbial feedbacks within new vegetation types determine long-term trajectories of nutrient dynamics (Melvin et al. 2015), ecosystem C storage (Johnstone et al. 2010a, Alexander and Mack 2015, Alexander and Mack 2016) and resultant feedbacks to regional or global climate (Randerson et al. 2006).

Key working group objectives:

1. Identify deterministic (e.g., state factor) and stochastic (e.g., fire weather) controls and their interactive effects on spatial and temporal variations in fire characteristics (e.g., size, severity, spatial heterogeneity).
2. Characterize fire effects on C biogeochemistry, permafrost, hydrology, flora, fauna, and ecosystem services and determine how they vary across ABoVE regions.
3. Characterize fire impacts on ecosystem services, including those that impact both local and global stakeholders.

4. Identify regional shifts in fire regimes and, based on objectives 1 and 2, refine models to project impacts on C-biogeochemistry, permafrost, hydrology, flora, fauna, and ecosystem services.
5. Work with regional land and fire managers to create “use-inspired science”: knowledge and products that address emergent management issues in a warming climate.

3.3.2 LOCATIONS

Current field plans include measurement campaigns in the following regions (Figure 1):

1. Tundra in the **Noatak River Valley of Northwestern Alaska**, where there is a robust recent and paleo-record of small, overlapping fires during the Holocene and permafrost is warm (~ -2 degrees C at the surface) but continuous. Loboda’s group is working in this region.

2. Tundra on the **Seward Peninsula**, Alaska, where there is a long record of large and moderate-sized overlapping fire events and permafrost is warm and discontinuous. Loboda’s group is working in this region; in addition, there is a major field campaign from the Arctic NGEE group that will potentially overlap with some of Loboda’s sites.

3. Moist acidic tussock and shrub tundra on the **North Slope of the Brooks Range**, Alaska, where fire has been infrequent or absent during the Holocene and permafrost is cold (~ -10 degrees C at the surface) and continuous). Loboda and Rocha’s groups are working in this region.

4. Moist acidic tussock and shrub tundra near altitudinal treeline on the north slope of the **Alaska Range in Denali National Park**, where permafrost is warm (~0 degrees C) and degrading. Mack’s group is working in this region and collaborating with Denali National Park and Preserve, and the Alaska Parks Regional Monitoring Network.

5. Boreal forests, woodlands and wetlands in the **Northwest Territories**, Canada, that span the taiga plans and shield ecoregions near Yellowknife, and burned in the record 2014 fire year. Mack and Bourgeau-Chavez’s groups are working in this region.

6. Boreal forests and woodlands in **Northern Saskatchewan**, Canada, that burned in the record 2014 fire year. Rogers and Mack’s groups are working in this region.

7. Boreal forest sites in Interior Alaska and arctic tundra sites on the North Slope where group members have worked in the past.

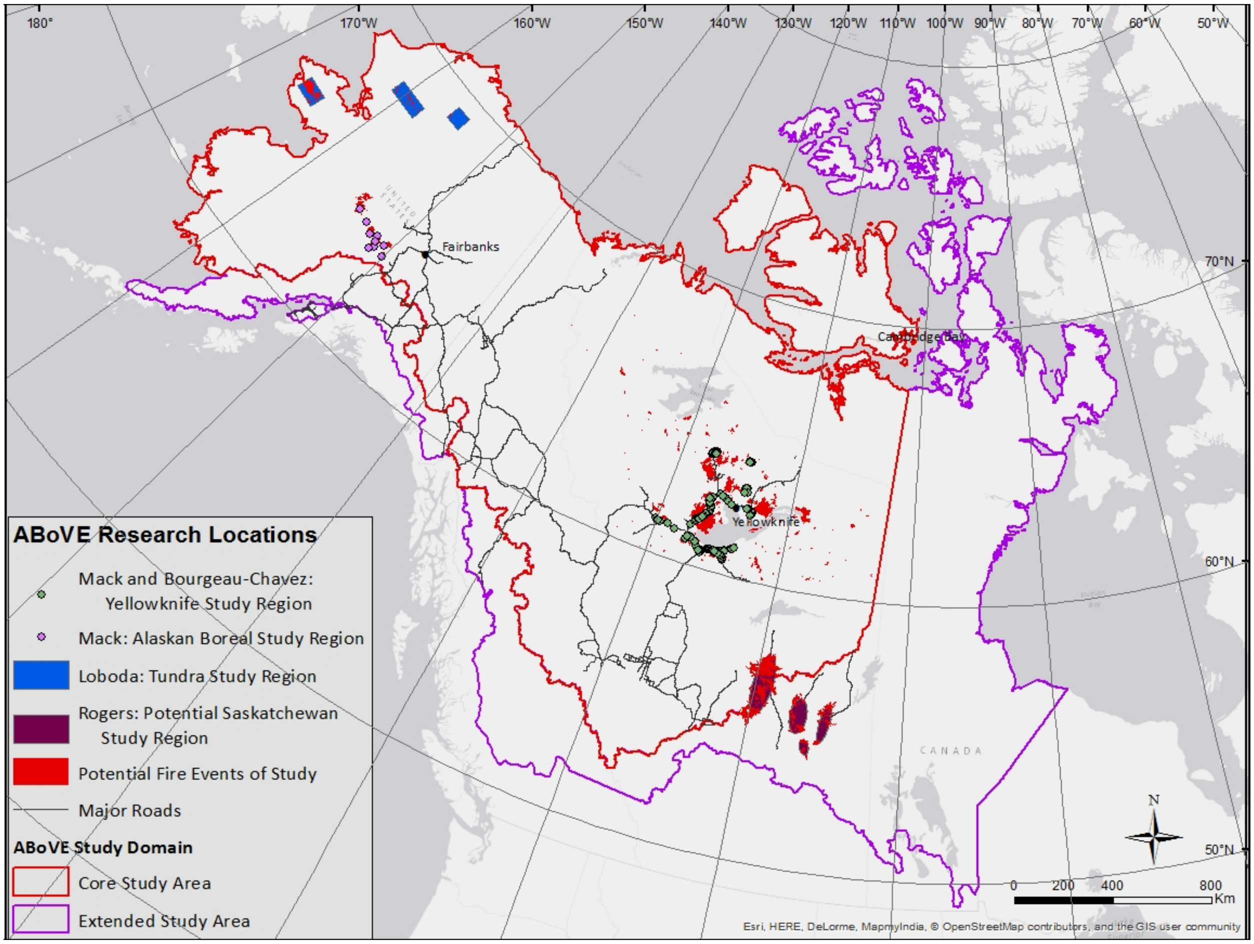

Figure 1: Locations of working group study plots and regions.

3.3.3 FIELD MEASUREMENTS

The varying objectives across projects require that field measurements be carried out with a diverse suite of methods and at a range of spatial scales. All projects will characterize some aspects of (1) pre- and post-fire vegetation structure and soil organic layer depth, (2) permafrost and site or soil drainage, and (3) some qualitative visual index of fire "severity." Some methodological approaches are being used by multiple projects, including the adventitious root method for reconstructing pre-fire soil organic layer depth in black spruce forests (Kasischke et al. 2008, Boby et al. 2011) and the tussock meristem method for reconstructing pre-fire soil organic layer depth in oldgrowth (i.e., undisturbed) moist acidic tundra (Mack et al. 2011). There is ongoing discussion of collaborative measurements of some soil characteristics, such as organic layer bulk density, C and N concentration, and radiocarbon age of the burned surface, across groups. In particular, consistent approaches are needed for measuring soil moisture to increase cross-group comparability. Project-specific measurements are described below.

Mack: Within each study region (Denali Tundra, NWT), this group will use geospatial data to define a domain of inference for sampling (Hurlbert 1984).Within that domain, they will randomly sample the landscape in a network of extensive field sites that be used to extrapolate results. Nested within this network will be a suite of intensive field sites stratified to cover key topo-edaphic units and fire behavior classes. This suite of sites will enable robust testing of hypotheses about controls over legacy C loss and ecosystem response, while the extensive sites will enable scaling of results to the study domain. Field and statistical methods are exhaustively described in Mack's ABoVE proposal and do not bear repeating here. In short, environmental variables (Table 1) will be measured in all burned sites to provide landscape context and link sites to geospatial data layers. For measurements that vary within sites, random and replicate sampling will provide uncertainty estimates that reflect sampling effort. For all field measured variables, sampling efforts will be based on power analyses of these metrics from past work in tundra and forest sites. Rapid surveys of canopy consumption and depth of burning (Boby et al. 2011, Mack et al. 2011) will be carried out in all sites to yield estimates of pre- and post-fire pools of plant and SOL C and calculation of combustion losses. In all burned sites, p*ost-fire vegetation regeneration* from resprouters and seedlings will be estimated, as well as understory pre-fire vegetation composition.

In intensive sites, depth, bulk density and C concentration of soil organic matter and the radiocarbon signature of moss macrofossils in the residual SOL will be measured. Using these data, they will estimate both the magnitude and proportion of *legacy C loss.* Site surface will be mapped with differential GPS to assay microtopographic variation in years 1 and 3 of the study so that initial post-fire *subsidence and change in drainage* can be determined. Finally, natural seed rain will be sampled and a seed addition experiment will be used to test for *seed limitation of regeneration* by dominant tree and shrub species.

Table 1. *Example of environmental variables that will be measured in each sample site, measurement units and within-site sample size (n).*

Variable	Units	n
Datum	WGS84	4
Latitude	Decimal degrees	4
Longitude	Decimal degrees	4
Elevation	MSL	4
Permafrost	Class	4
Thaw depth	cm to frozen soil	20
Rock density	% rock hits in thaw depth probes	20
Slope position	Category	1
Aspect	Degrees	1
Contour type	Class	1
Bedrock type	Class	1
Landform	Class	1
Pre-fire vegetation	Class	1
Soil moisture class	Class	1
Mineral soil texture	% sand, % silt, % clay	5
Mineral soil pH	Log $[H^+]$	5
Composite Burn Index	Scalar	1
Stand age (trees)	Years	10

Estimates of combusted canopy and soil C pools depend upon empirical bi-variate relationships developed in unburned sites between (1) biometry and plant biomass, (2) biometry and SOL depth, and (3) SOL depth, bulk density and C concentration. Although we have developed these relationships for old-growth arctic tundra (Mack et al. 2011) and black spruce forests in Interior Alaska (Boby et al. 2010), preliminary data suggest that relationships in other regions may have different slopes and intercepts (Mack unpublished data). New regional samples will be added to our existing data sets, or new relationships will be developed outright by sampling biometric markers and soils in 10 or more widely-dispersed unburned sites paired with burned sites so that they fall within the same general domain of inference.

Bourgeau-Chavez: 2016-18 summer field data will be collected by crews of 2-4 people. New sites will be visited and some old sites re-visited each summer. Unburned sites will be sampled in 40 x 50 m plots for ecosystem type and general characterization of biomass, stand density, etc., for land cover mapping. Burned sites will be sampled, collecting time-stamped data, for pre-burn ecosystem type, post-burn ground fuel loading, burn severity, depth of burn, post-fire vegetation regrowth, soil moisture, pre-burn biomass, depth to frozen ground and stand age.

Loboda: point sample (PS) location and GPS-linked photos in each cardinal direction and nadir. Variables to be collected include: (1) Active layer depth (thaw depth); (2) soil moisture at 6 cm and 12 cm; (3) soil temperature; (4) depth of SOL (unaffected by permafrost); (5) exposed soil profile; (6) ocular assessment of above ground vegetation within a 10 m square plot; (7) fractional cover of woody vegetation, herbaceous vegetation, mosses, and lichens; (8) number of trees and shrubs > 0.5 m in height; (9) above ground biomass estimates: tussock measurements (Mack et al. (2011) plus an additional uncompacted tussock crown measurement, which will measure the outmost extent of tussock crown in 2 cross-cutting directions to assess soil exposure to direct heating) and woody stem count and diameter within a 1 m square plot (a standard measurement linked to biomass estimates).

Rogers: Field measurements will focus primarily on aboveground and belowground combustion. They will be taking typical tree measurements such as DBH, species, and % combustion of cones, needles, small and large branches, and boles at transects. Soil pit measurements will include the depth to mineral soil, adventitious roots (as appropriate), and depths of specific soil horizons. Lab analyses will further quantify dry weight, bulk density, %C, %N, etc. Tree cores will be collected at new field sites and existing permanent sample plot (PSP) locations, working with Mack-01 to assess radiocarbon age in some soil profiles. Collaborators from the Randerson lab at UC Irvine will also be working with our group to collect leaf samples for elemental analysis, and to establish aerosol samplers (HIVOL-AMCLD) with PM2.5 plates at two locations for the entire summer of 2016 (at least).

3.3.4 REMOTE SENSING

Table 2. *Summary of remote sensing products that will be used by the working group.*

Variable	**Remote Sensing or Ancillary Data Source**	**Resolution**	**Team**
Vegetation Ecosystem Types	WorldView-2	1 m	Bourgeau-Chavez
Vegetation Ecosystem Types	Landsat	30 m	Bourgeau-Chavez, Loboda
Vegetation EcosystemTypes	PALSAR, Radarsat-2, Sentinel-1	20 m	Bourgeau-Chavez, Loboda
Vegetation Types	CAVM (Walker et al 2005)	30 m	Loboda

Years since fire	ALFD, NLFD (Canada)		Loboda, Bourgeau-Chavez, Rogers, Mack
Years since fire	tundra fire history (pre-ABoVE proposal, PI Loboda)	30 m	Loboda
Burn Severity	Landsat, MODIS	30 m	Bourgeau-Chavez, Rogers, Mack, Loboda
Fire Progression	MODIS	500 m	Bourgeau-Chavez, Rogers, Mack, Loboda
Elevation	Alaska IfSAR DEM	3 m	Loboda
Slope	Alaska IfSAR DEM	3 m	Loboda
Aspect	Alaska IfSAR DEM	3 m	Loboda
Drainage	Alaska IfSAR DEM	3 m	Loboda
Elevation	NGA (Morin)	2 m	Bourgeau-Chavez, Rogers, Mack, Loboda
Soil exposure	Landsat	30 m	Loboda
Thermal brightness	Landsat	30 m	Loboda
Surface albedo	Landsat, MODIS	30, 500 m	Loboda, Rogers, Mack
Vegetation greenness	Landsat	30 m	Loboda
Soil moisture	Radarsat-2, Sentinel-1, PALSAR-2	30 m	Loboda, Bourgeau-Chavez
Surface roughness and vegetation biomass	Radarsat-2, Sentinel-1, PALSAR-2	30 m	Loboda, Bourgeau-Chavez
Rate of fire spread	MODIS	500 m	Loboda
Fire Radiative Power	MODIS	500 m	Loboda
BRDF	MODIS	500 m	Rogers
Landcover/Treecover	MODIS, Landsat	500, 30 m	Rogers
Snow Cover	MODIS	500 m	Rogers, Mack
Active Fires	MODIS	1 km	Rogers
Pre- and Post-Fire	G-LiHT	cm	Rogers
Freeze-Thaw	SMAP	36 km	Mack
Land-Surface Temperature	MODIS	500 m	Mack
Proximity to Water	Landsat derived water body maps (Carroll et al. 2015)	30 m	Mack

Mack: Remote sensing (Table 2) and geospatial datasets (Table 3) will be used to (1) define the domain of inference for sample selection, and (2) extend the inferences from the field site measurements to the landscape. In order to define the domain of inference and select both extensive and intensive field sites, we will overlay a number of geospatial data layers. These will include a wide range of geospatial predictors, some of which may become available as part of the product development of selected ABoVE ST members, as well as via synergies with other disturbance-oriented proposals addressing burn severity, combustion and post-disturbance recovery (e.g. French et al., Loboda et al., and Rogers et al.).

Table 3. *Examples of geospatial variables that Mack will use for defining the domain of inference and for scaling field data to landscapes and regions.*

Dynamic variables
- Landscape-freeze thaw status (e.g. PalSAR, SMAP)
- Surface wetness (e.g. MEASURES products)
- Vegetation productivity (Landsat/MODIS VIs)
- Snow covered area (MODIS product)
- Surface albedo (MODIS products)
- Land surface temperature (MODIS products)

Less dynamic variables
- Land cover class (multiple sources)
- Vegetation cover (multiple sources)
- Thermokarst class (e.g., Belshe et al. 2013)
- Vegetation cover (composition, type, density)
- Deciduousness (Landsat/MODIS, e.g. Beck et al 2011)
- Size of vegetation patches, shape metrics (edge/area)

Static variables
- Topography (slope, slope position, aspect, insolation)
- Surficial geology (as per ABoVE CEP)
- Ecoregion classification (as per ABoVE CEP)
- Proximity to water feature (Carrol project water bodies)
- Drainage class (primary, secondary, etc.)

Fire variables
- Date of burning
- Fire weather at time of burn
- Rate of burning (MODIS hot spot), smoldering evidence
- Overlap with past burn--% area, time
- Distance to burn edge

Integration and scaling of geospatial data, products will be developed using decision rules based on a combination of boosted regression and classification trees within the *random forests* software package. The decision rules will, in simplest terms, be predictor variable-specific threshold values based on the terminal nodes of the decision trees. The categories will be landscape units with a ranking relative vulnerability of legacy C loss. A second approach to achieve this end goal will make use of image segmentation software (such as eCognition) to derive polygons associated with suites of attributes that define the landscape units. Coupling the segmentation analysis with various field measurements will allow us to characterize spatial and temporal variability within and between segments, and their statistical separability, using the geospatial data layers and properties we are measuring on the ground. Both *random forests* and segmentation approaches will allow us to extend the site-level work to the landscape, across variable extents (i.e. study regions and the broader ABoVE domain).

Bourgeau-Chavez: PALSAR-2, Radarsat-2, Sentinel-1, and Landsat spaceborne remote sensing as well as Worldview-2 will be used. Soil moisture will be collected coincident with planned spaceborne SAR data collections. Planned geospatial data products include peatland type maps from SAR and Optical fusion, burn severity maps based on algorithms specific to uplands and peatlands using Landsat, soil moisture maps post-burn based on SAR. This is linked to post-fire regrowth.

Loboda: Space-borne remote sensing plans include two primary uses of moderate resolution optical and thermal (Landsat) and microwave (SAR) remotely sensed imagery. Landscape stratification for field data collection will be done with burn severity metrics (Landsat), summer rDNBR, and spring TCB. Satellite remotely-sensed data will also be used to identify metrics that can be used as explanatory variables for observed measurements, and to scale point source measurements to the landscape and the ecosystem as a whole. Landsat metrics include: soil exposure (spring TCB), surface thermal brightness (seasonal if possible), surface albedo, and vegetation greenness (NDVI). InSar metrics include: soil moisture and surface roughness. MODIS/VIIRS metrics include fire spread rate and fire Radiative Power.

Rogers: Existing space-borne remote sensing from MODIS and Landsat will be used for various project analyses. MODIS active fires, surface reflectance, land cover, and tree cover will be used in emissions modeling. MODIS albedo, BRDF parameters, and snow cover will be used in analysis of spring albedo forcings. Landsat surface reflectance and tree cover (e.g. Sexton et al., 2013) will be combined with MODIS for emissions modeling. Several ancillary data sets will also be used, some derived in part from remote sensing. For airborne remote sensing, exact data use will depend on the instruments and experimental setup, which outlined in the Airborne Science WG section but will also depend upon airborne science proposal selections. A small amount of existing G-LiHT data collected pre- and post-fire over the 2014 Funny River fire in the Kenai Penninsula, AK will be used for preliminary analysis of capabilities. Primary planned geospatial data products include fire-climate forcings from greenhouse gases, spring albedo, and aerosols at 450m resolution from fires in the domain during 2002 – 2011. They will also produce burned area pixels and severity from 1950 – 2016 (inferred pre-MODIS era using derived statistical relationships).

3.3.5 GEOSPATIAL DATA PRODUCTS

Working group members plan a diverse array of geospatial data products, which are described in Table 4.

Table 4: *Planned geospatial data products by project PI.*

Product	Project PI	Variable	Spatial domain	Resolution	Time period
Vegetation	Bourgeau-Chavez	peatland types	NWT	50 m	pre-2014
Burned area	Loboda	burned/unburned	> 60°N	30 m	1984-2015
	Loboda	burned/unburned	> 60°N	1 km	1982-2003
	Loboda	burned/unburned	> 60°N	500 m	2001-2015
	Loboda	burned/unburned	> 60°N	375 m	2012-2015
	Rogers	burned/unburned	ABoVE domain	500 m	2001-2015
Fire severity	Bourgeau-Chavez	fire severity	NWT	30 m	2014-2015
	Loboda	dNBR, Tasseled Cap Brightness	> 60°N	30 m	1984-2015
	Rogers	dNBR, C combustion	ABoVE domain	500 m	2001-2015
Fire progression	Loboda	date of burn, residual burning	> 60°N	1 km	2001-2015
	Rogers	date of burn, residual burning	ABoVE domain	1 km	2001-2015
Active fire	Loboda	active fire locations	> 60°N	1 km	1982-2015
	Loboda	active fire locations	> 60°N	375 m	2012-2015
Fire-climate forcing	Rogers	greenhouse gas emission forcings	ABoVE domain	500 m	2001-2015
	Rogers	albedo forcings	ABoVE domain	500 m	2001-2011
	Rogers	fire aerosol forcings	ABoVE domain	500 m	2001-2015

	Rogers	net forcings	ABoVE domain	500 m	2001-2011
Vulnerability	Bourgeau-Chavez	high severity burning	NWT	20 m	
	Mack	legacy C vulnerability	Denali NP, NWT	30 m	
	Mack	C cycle resilience/vulnerability	Denali, NWT	30 m	
	Rogers	warming/cooling potential	ABoVE domain	500 m	
Snow	Loboda	snow onset, offset	> 60°N	1 km	2003-2012
Clouds	Loboda	fractional cloud cover	> 60°N	1 km	2003-2012
Field measurements	Bourgeau-Chavez, Loboda, Mack, Rogers	see Table 1	see Table 1	see Table 1	see Table 1

3.3.5 MODELING

All groups will employ statistical modeling techniques that range from multiple linear regression to machine learning to hypothesis testing frameworks, such as structural equation modeling.

Bourgeau-Chavez: focus on creating products (parameter values and validation datasets) for CanFIRE (e.g. fuel loading, burn severity, peatland and other land cover types) to estimate fire emissions and fire effects for uplands/peatlands, but they should be suitable for other ecosystem models as well.

Rogers will employ statistical modeling (i.e. multiple linear regression and machine learning) in various components of the research, including modeling combustion, deriving landscape facets, and characterizing trajectories of landscape succession and post-fire spring albedo. However, they will also engage in more intensive process modeling. Their estimates of post-fire C dynamics will be based on land surface modeling, either with the Community Land Model or the UVAFME gap model. For aerosol effects, they will be running the Community Earth System Model with an online radiation diagnostics tool. They may also leverage ongoing efforts in the area using the WRF-STILT transport model at much finer resolution (3 – 10 km).

3.3.6 KNOWLEDGE GAPS AND NEEDS

The group identified the following knowledge gaps:

- Regional coverage is needed for ecoregions with emerging fire dynamics, including the Yukon-Kuskokwim Delta, lodgepole pine forests in the Yukon Territory, and treeline and tundra in Northern Canada.
- Most funded ABoVE studies are using a gradient approach to infer impacts of an intensifying fire regime and are not assessing synoptic change. Studies are needed that synthesize retrospective and contemporary data for regions where fire dynamics appear to be intensifying, such as the NWT or Alaskan tundra.
- Maps that harmonize vegetation and soil classifications across the US/Canadian border are

needed.

- Studies are needed that link changing fire regimes to population dynamcis of animals such as caribou and moose.
- Studies are needed of fire behavior dynamics that include predictions of smoke production and behavior.
- Studies are needed that explicitly address the vulnerability of permafrost carbon to fire disturbance.
- Studies are needed that expand beyond wildfire to other key disturbance agents, such as abrupt permafrost thaw, outbreaks of insects and pathogens, and drought-induced tree mortality.

LITERATURE CITED

Alexander, H., and M. Mack. 2015. A Canopy Shift in Interior Alaskan Boreal Forests: Consequences for Above- and Belowground Carbon and Nitrogen Pools during Post-fire Succession. Ecosystems:1-17.

Alexander, H. D., and M. C. Mack. 2016. A canopy shift in interior Alaskan boreal forests: consequences for above- and belowground carbon and nitrogen pools during post-fire succession. Ecosystems.

Boby, L. A., E. A. G. Schuur, M. C. Mack, J. F. Johnstone, and D. L. Verbyla. 2010a. Quantifying fire severity, carbon and nitrogen emissions in Alaska's boreal forests. Ecological Applications **26**:1633-1647.

Boby, L. A., E. A. G. Schuur, M. C. Mack, D. Verbyla, and J. F. Johnstone. 2010b. Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest. Ecological Applications **20**:1633-1647.

Harden, J. W., S. E. Trumbore, B. J. Stocks, A. Hirsch, S. T. Gower, K. P. O'Neill, and E. S. Kasischke. 2000. The role of fire in the boreal carbon budget. Global Change Biology **6 (Suppl.)**:174-184.

Hobbie, S. E., J. P. Schimel, S. E. Trumbore, and J. R. Randerson. 2000. A mechanistic understanding of carbon storage and turnover in high-latitude soils. Global Change Biology **6**:196-210.

Hurlbert, S. H. 1984. Pseudoreplication and the design of ecological field experiments. Ecological Monographs **54**:187-211.

Johnson, E. A. 1996. Fire and vegetation dynamics: studies from the North American boreal forest. Cambridge University Press.

Johnstone, J., L. Boby, E. Tissier, M. Mack, D. Verbyla, and X. Walker. 2009. Postfire seed rain of black spruce, a semiserotinous conifer, in forests of interior Alaska. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **39**:1575-1588.

Johnstone, J. F., F. S. Chapin, T. N. Hollingsworth, M. C. Mack, V. Romanovsky, and M. Turetsky. 2010a. Fire, climate change, and forest resilience in interior Alaska. Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere **40**:1302-1312.

Johnstone, J. F., and F. S. Chapin, III. 2006. Effects of soil burn severity on post-fire tree recruitment in boreal forest. Ecosystems **9**:14-31.

Johnstone, J. F., T. N. Hollingsworth, F. S. Chapin, III, and M. C. Mack. 2010b. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. Global Change Biology **16**:1281-1295.

Jorgenson, M. T., J. Harden, M. Kanevskiy, J. O'Donnell, K. Wickland, S. Ewing, K. Manies, Q. L. Zhuang, Y. Shur, R. Striegl, and J. Koch. 2013. Reorganization of vegetation, hydrology and soil carbon after permafrost degradation across heterogeneous boreal landscapes. Environmental Research Letters **8**.

Kasischke, E. S., N. L. Christensen, and B. J. Stocks. 1995. Fire, global warming, and the carbon balance of boreal forests. Ecological Applications **5**:437-451.

Kasischke, E. S., M. R. Turetsky, R. D. Ottmar, N. H. F. French, E. E. Hoy, and E. S. Kane. 2008. Evaluation of the composite burn index for assessing fire severity in Alaskan black spruce forests. International Journal of Wildland Fire **17**:515-526.

Lantz, T. C., S. V. Kokelj, S. E. Gergel, and G. H. R. Henry. 2009. Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. Global Change Biology **15**:1664-1675.

Mack, M. C., M. S. Bret-Harte, T. N. Hollingsworth, R. R. Jandt, E. A. G. Schuur, G. R. Shaver, and D. L. Verbyla. 2011. Carbon loss from an unprecedented Arctic tundra wildfire. Nature **475**:489-492.

Pizano, M. C., A. F. Baron-Lopez, E. A. G. Schuur, K. G. Crummer, and M. C. Mack. 2014. Effects of thermo-erosional disturbance on surface soil carbon and nitrogen dynamics in upland arctic tundra. Environmental Research Letters **9**.

Randerson, J. T., H. Liu, M. G. Flanner, S. D. Chambers, Y. Jin, P. G. Hess, G. Pfister, M. C. Mack, K. K. Treseder, L. R. Welp, F. S. Chapin, J. W. Harden, M. L. Goulden, E. Lyons, J. C. Neff, E. A. G. Schuur, and C. S. Zender. 2006. The impact of boreal forest fire on climate warming. Science **314**:1130-1132.

Schuur, E. A. G., J. Bockheim, J. G. Canadell, E. Euskirchen, C. B. Field, S. V. Goryachkin, S. Hagemann, P. Kuhry, P. M. Lafleur, H. Lee, G. Mazhitova, F. E. Nelson, A. Rinke, V. E. Romanovsky, N. Shiklomanov, C. Tarnocai, S. Venevsky, J. G. Vogel, and S. A. Zimov. 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. BioScience **58**:701-714.

Schuur, E. A. G., J. G. Vogel, K. G. Crummer, H. Lee, J. O. Sickman, and T. E. Osterkamp. 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature **459**:556-559.

Shur, Y. L., and M. T. Jorgenson. 2007. Patterns of permafrost formation and degradation in relation to climate and ecosystems. Permafrost and Periglacial Processes **18**:7-19.

Turetsky, M. R., E. S. Kane, J. W. Harden, R. D. Ottmar, K. L. Manies, E. Hoy, and E. S. Kasischke. 2011. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience **4**:27-31.